Experimental Demonstration of Delta-sigma Modulation Supported 65536-QAM OFDM Transmission for Fronthaul/WiFi Applications

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Abstract *We demonstrate the digitization and transmission of 65536-QAM OFDM signals over 20-km fiber via 10-Gbaud PAM-4 IM-DD channel. SNR of 57.7dB is achieved for baseband signals with standard PAM-4 and the proposed SNR-improved delta-sigma digitization.*

Introduction

With the increase in demand for high-speed applications, the volume of data usage from end users is growing rapidly, so higher requirements are put forward for mobile fronthaul (MFH). Current MFH networks are mainly operated based on the Common Public Radio Interface (CPRI) protocol, which exhibits excellent tolerance against transmission impairments. However, due to its low spectral efficiency, CPRI becomes the bottleneck of digital MFH to support huge mobile data transmission [1]. As a solution to this issue, the delta-sigma modulation-based MFH architecture has been widely investigated [2,3], because of its high spectral efficiency and robustness against noise. What's more, this architecture enables delivery of analog signal through digital ports without any digital-to-analog converters (DACs) [4]. Lots of work has been done around delta-sigma modulation to improve the SNR, including the employment of high order modulators [5], multiple quantization bits [6] and new feedback structures [7]. However, due to the in-band noise, SNR can only reach ~30 and ~40dB with 1-bit and 2-bit quantization, respectively, with an oversampling ratio (OSR) of 8, which limits the enhancement of spectral efficiency [1],[7].

In order to achieve higher data rate within a fixed bandwidth, it is necessary to send more bits on each symbol [8]. In 802.11ax, the IEEE standard for WiFi 6, 1024-QAM modulation is selected as the main modulation format [9]. And 4096-QAM has already been used in the Qualcomm FastConnect 6900 and 6700 Mobile Connectivity Systems [10]. Furthermore, 802.11be (WiFi 7) is expected to continue upgrading the modulation order, directly using 4096-QAM or higher orders, which will expand the transmission data capacity and challenge the current transmission systems of ultra-high-order QAM.

However, some non-ideal factors of analog architectures limit the recovery of high order QAM signal, including the accuracy of DACs and analog-to-digital converters (ADCs), IQ imbalance and nonlinear distortion [11]. Thus, realizing high order QAM with a low-cost architecture is challenging.

In this paper, in order to achieve ultra-high order QAM， we have proposed an SNR-improved delta-sigma digitization scheme to replace the traditional 2-bit quantization in digital MFH, which can significant improve output signal SNR. We demonstrated the digitization and transmission of 65536-QAM baseband OFDM signal over 20-km fiber with standard 10-Gbaud PAM-4 signal, with an SNR of 57.7 dB. In addition, we also realize a transmission of 65536-QAM IF signal (with an SNR of 55.7 dB), which shows great flexibility towards different wireless frequency bands for the 5G and beyond applicaitons.

Operation Principles

Delta-sigma modulation can deliver analog signal through digital ports, and is widely investigated for fronthaul applications. Delta-sigma modulation oversamples analog signal to expand its Nyquist zone, and then pushes more quantization noise out of the signal band through noise shaping. Thus, analog signal can be converted to OOK or PAM-4 with one or two bits. The received signal can be easily retrieved by using filters at the receiver side without DACs [1],[2].

In order to reduce in-band noise (IBN), this paper employs the key concept of delta-sigma modulation, and proposes an SNR-improved delta-sigma digitization scheme, which is shown in Fig. 1(a-d). IBN-I, which can be retrieved by filtering the difference between analog signal and the 1-bit sequence, remains after delta-sigma

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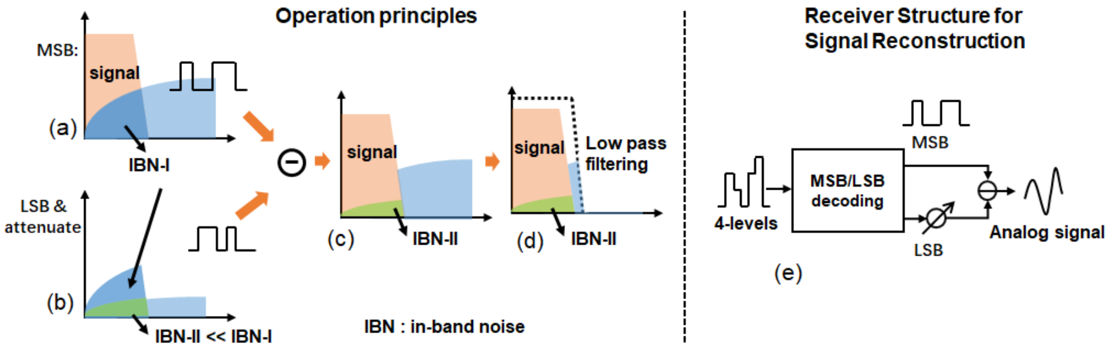

Fig. 1: (a-d) Operation Principles of the SNR-improved delta-sigma digitization. (e) Receiver structure for signal reconstruction

digitization, as is shown in Fig.1 (a). Then, delta-sigma modulator converts IBN-I to a 1-bit sequence, which acts as the LSB. Since IBN-I should be amplified to fit the input requirement of delta-sigma modulators, LSB is derived and calculated from IBN-I. In this scheme, the newly added IBN-II is much smaller than IBN-I. After delta-sigma digitization, Gray mapping converts two 1-bit sequences to four levels, which can be delivered to the remote site with standard PAM-4 devices. At the receiver, LSB needs power adjustment corresponding to the amplification at the transmitter. Then two bit sequences are fed into the differentiator and the out-of-band noise is filtered out to recover original analog signal with trivial IBN-II left, as is shown in Fig. 1(e), bringing about a much better noise shaping performance.

Tab. 1: Simulation results of baseband signals through different schemes based on delta-sigma modulation with OSR=8

Schemes	1-bit	2-bit	SNR-improved
SNR (dB)	32	40	57.7
Max M-QAM	256	1024	65536

*Max M-QAM is measured under the requirement of BER<1e-4

Tab. 1 shows simulation results of baseband signals with OSR=8 based on 1-bit, 2-bit and the proposed SNR-improved delta-sigma digitization, respectively. All the simulations mentioned above use a fourth-order delta–sigma modulator based on cascade-of-resonators feedforward (CRFF) structure, one of the most classical structure of delta-sigma modulators. As shown in Tab. 1, it is obvious that applying SNR-improved delta-sigma digitization brings great improvement of SNR. And only a low noise circuit is needed to implement the above procedures.

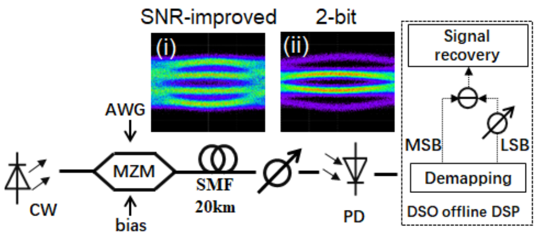

Fig. 2: Experimental setup

Experiment setup and results

Fig. 2 shows the experimental setup of the 10Gbaud IM/DD PAM-4 system for verifying the performance of the SNR-improved delta-sigma digitization-based digital fronthaul architecture. For comparison, the conventional 2-bit delta-sigma quantization scheme-based digital MFH is also demonstrated. Due to the Gaussian distribution of OFDM signals, the PAM-4 signal after 2-bit digitization has unequal symbol distribution, as is shown in insert (ii). Different from the 2-bit delta-sigma quantization, eye diagram of the SNR-improved delta-sigma digitization-based PAM-4 signal shown in insert (i) has even distribution. Tab. 2 lists OFDM parameters of three cases. In the transmitter, the OFDM signal is generated offline with FFT size of 1024, in which 900 subcarriers are loaded with

Tab. 2: OFDM parameters of baseband and IF signals used in experiments and results

Case	scheme	Parameters					result		
		Sampling rate (GHz)	FFT size	Date Subcarriers	Center frequency (GHz)	Modulation (QAM)	SNR (dB)	EVM	BER
I	2-bit quantization	1.25	1024	900	baseband	1024	40	1%	1.56e-5
II	SNR-improved	1.25	1024	900	baseband	65536	57.7	0.13%	1.77e-5
III	SNR-improved	0.5	1024	900	3.5	65536	55.7	0.16%	1.9e-4

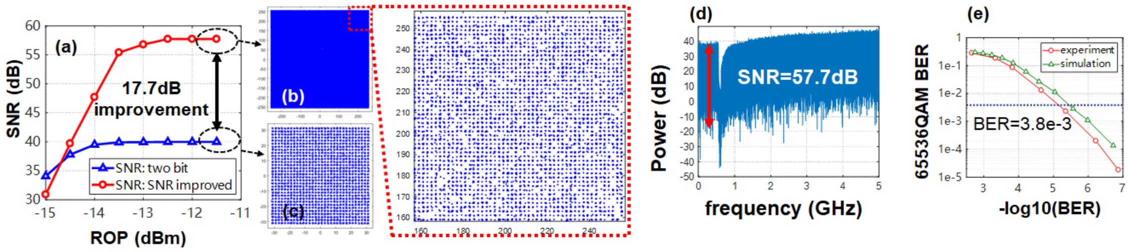

Fig. 3: Experimental results of Case I & II: baseband signal with 1024-QAM and 65536-QAM. (a) SNR vs received optical power. (b,c) Constellations after 20-km fiber at received optical power of -12dBm (d) electrical spectra of recovered baseband signal with 65536-QAM of case II (e) 65536-QAM BER vs PAM-4 BER

data. After two kinds of delta-sigma digitization, the delta-sigma modulated bit sequences are output by an arbitrary waveform generator (AWG Keysight M8195A) working at 60GSa/s, which only operates in a 2-bit output manner. The intensity modulation is fulfilled by a 1550-nm laser and a Mach-Zehnder modulator (MZM). 10Gbaud Optical PAM-4 signal is transmitted over 20km standard single mode fiber (SSMF). At the receiver, the optical signal is detected by a 40G photodiode (PD). PAM-4 utilizes 5-tap feed forward equalization (FFE) for signal recovery. The electrical signal is acquired by an oscilloscope at 60 GSa/s and downloaded for signal decoding and recovery. In this experiment, we use offline digital signal processing (DSP) to achieve signal reconstruction. Circuit design with low noise is required in practical implementation. Offline DSP includes demapping, attenuation, differentiation and signal recovery. 4-levels signal is converted to two 1-bit sequences, and the LSB of them needs to be attenuated corresponding to the amplification ratio at the transmitter. Then the two bits are fed into a differentiator to filter out the out-of-band noise to recover original analog signal with trivial noise.

Fig. 3(a) illustrates the SNR performance versus ROP of received OFDM signal with 1024-QAM and 65536-QAM modulation format. Since PAM-4 signal contains quantization noise after delta-sigma modulation, the SNR converges at a certain value at higher ROP. At ROP=-12dBm, the SNR-improved delta-sigma digitization achieves SNR of 57.7dB, which is sufficient to support 65536-QAM, and the corresponding BER is 1.56e-5, as is shown in Tab. 2. Fig. 3(d) shows the electrical spectra of the recovered baseband signals with 65536-QAM at best performance. With the same MFH rate, however, SNR of the 2-bit quantization scheme can only reach 40dB, which can only support up to 1024-QAM. The SNR improvment is 17.7dB. Constellations of the 1024-QAM and 65536-QAM OFDM signal generated by two kinds of delta-sigma digitization at ROP of −12 dBm are shown in Fig. 3 (b) and (c), respectively, showing that the SNR-improved delta-sigma digitization performs much better than conventional 2-bit delta-sigma quantization scheme. Since the SNR-improved delta-sigma digitization applies 1-bit quantization, the SNR of 65536-QAM signals deteriorates severely under low ROP. In experiments, error-free transmission of 10-Gbaud PAM-4 over 20km SSMF is achieved. The impact of BER performance upon the digital fronthaul is also investigated. Fig. 3(e) shows the influence of PAM-4 BER on the BER of received 65536-QAM signal. The proposed digital MFH can support 65536-QAM signal without exceeding the 7% FEC threshold (BER=3.8e-3), if PAM-4 BER is below 6.3e-6. We also tested the transmission and recovery of a IF signal with 65536-QAM at the center frequency of 3.5GHz. The best achievable BER of 1.9e-4 is obtained at ROP=-12dBm, which satisfies the BER requirement of 7% FEC threshold. In case III, OSR and bandwith are set as 10 and 500MHz, respectively.

Conclusions

For the first time, we demonstrated the digitization and transmission of 65536-QAM OFDM signals over 20-km fiber via PAM-4 IM-DD channel. Recovery of baseband and IF signal proves superior functionality and flexibility of this architecture, which meets the requirements of 5G fronthaul.

Acknowledgements

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